

Onset of Deconfinement in Nucleus-Nucleus Collisions

- Past, Present and Future -

Marek Gaździcki¹

Institut für Kernphysik, Universität Frankfurt, Germany and
Swietokrzyska Academy, Kielce, Poland

In 2007 Mark I. Gorenstein celebrated his 60th birthday. This report is dedicated to Mark and it sketches the results obtained during the past ten years of our collaboration and friendship. They concern search for and study of the onset of deconfinement in high energy nucleus-nucleus collisions.

invited talk given at the conference "New Trends in High Energy Physics",
Yalta, Crimea, September 15-22, 2007

¹E-mail: marek.gazdzicki@cern.ch

1 Remarks on the past

Since the very beginning Mark Gorenstein's scientific effort is devoted to:

- the development of the statistical theory of strong interactions,
- the development of statistical models of high energy nucleus-nucleus (A+A) collisions and
- the interpretation of the experimental data with the aim to uncover properties of strongly interacting matter.

This is well illustrated by quoting according to SPIRES Mark's first two papers from the beginning of 70s:

1) *Statistical-theory view on the dual-resonance model.*

M.J. Gorenstein, V.I. Makarov, V.A. Miransky, V.P. Shelest, G.M. Zinovjev (BITP, Kiev) . Lett.Nuovo Cim.3:347-350,1972.

2) *A fresh look at the statistical bootstrap model.*

M. I. Gorenstein, V.A. Miransky, V.P. Shelest, G.M. Zinovjev (BITP, Kiev) . Published in Phys.Lett.B45:475-477,1973.

his middle papers from the 90s, which mark a start of his travels abroad and a collaboration with physicists from all over the world:

103) *Phase-transitions in nuclear matter: Deconfinement of quarks and gluons?*

D.H. Rischke, M. I. Gorenstein, A. Schafer, H. Stoecker, W. Greiner (Frankfurt U.).

Given at 20th International Workshop on Gross Properties of Nuclei and Nuclear Excitations, Hirschegg, Austria, 20-25 Jan 1992.

104) *Excluded volume effect and the quark - hadron phase transition.*

J. Cleymans (Cape Town U. & Bielefeld U.), M. I. Gorenstein (Frankfurt U. & BITP, Kiev) , J. Stalnacke, E. Suhonen (Oulu U.). Published in Phys.Scripta 48:277-280,1993.

and finally his most recent two papers:

208) *Fluctuations in Statistical Models. M. I. Gorenstein . Sep 2007. Temporary entry e-Print: arXiv:0709.1428 [nucl-th].*

209) *Bose-Einstein Condensation of Pions. V. Begun, M. I. Gorenstein . Sep 2007. Temporary entry e-Print: arXiv:0709.1434 [hep-ph].*

The unique property of Mark's work is the clarity and simplicity in attempts to understand the objective properties of strongly interacting matter at high energy densities. Of particular interest for Mark are the questions:

- What are the phases of strongly interacting matter?
- Does the hypothetical high energy density state of strongly interacting matter, Quark Gluon Plasma (QGP), exist? and
- How do the transitions between the phases of strongly interacting matter look like?

In the mid-90s, when I met Mark for the first time during his stay at the University of Frankfurt, two predicted signals [1, 2] of QGP creation in A+A collisions were observed in central A+A collisions at the top SPS energy, 158A GeV. These were:

- the enhanced production of strange hadrons [3] and
- the suppressed production of J/ ψ mesons [4].

However, soon after it was realized that these signals are not specific for Quark Gluon

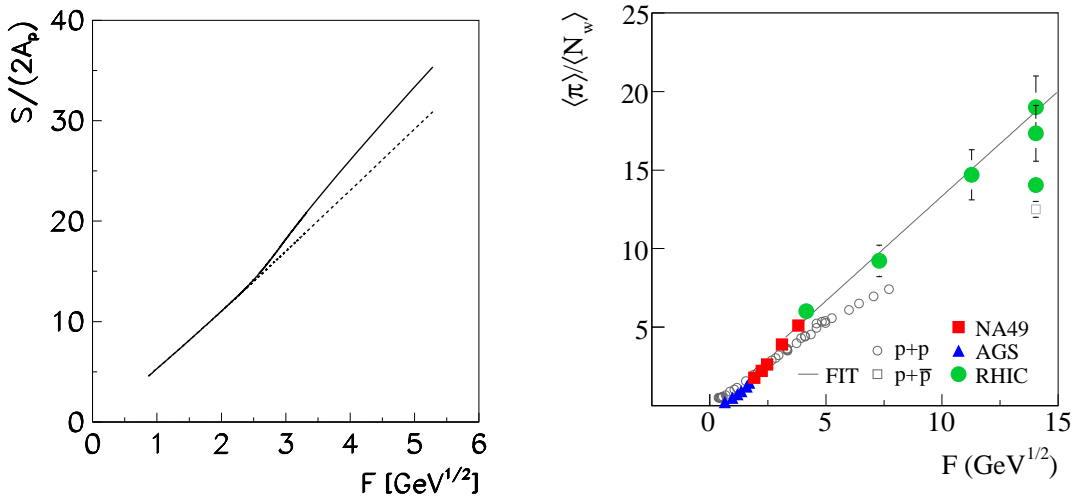


Figure 1: Left: The energy dependence of the early stage entropy calculated with SMES [5]. A change of the slope at $F \approx 2.25 \text{ GeV}^{1/2}$ ($\approx 30A \text{ GeV}$) indicates the onset of deconfinement. Right: Energy dependence of the mean pion multiplicity per wounded nucleon measured in central Pb+Pb and Au+Au collisions (full symbols), compared to the corresponding results from $p + p$ reactions (open circles) [11].

Plasma creation. In particular, the strangeness enhancement increases with decreasing collision energy [7] and production properties of J/ψ mesons can be explained assuming that it is produced together with other hadrons [8], e.g. via statistical hadronization process. On the other hand a comparison of the first results on nucleus-nucleus collisions at the top BNL AGS and CERN SPS energies [9] suggested an anomaly located between these two energies which might signal the onset of deconfinement at the early stage of nucleus-nucleus collisions. In numerous non-ending discussions we tried to find a consistent interpretation of the experimental results. It soon became obvious for us that an elegant explanation can be formulated provided that the commonly accepted paradigm [1] concerning a long-lasting dynamical stage of strange quark or hadron production in A+A collisions is replaced by an assumption of a very fast equilibration of the matter created at the early stage of collisions.

A model based on the later assumption was proposed by Mark and myself in 1997 [5] and we called it the Statistical Model of the Early Stage (SMES). Within this model the collision energy crosses the threshold energy needed for the creation of the mixed phase at the low SPS energies. The model predicted several contra-intuitive (within the old paradigm) signals of the onset of deconfinement. Before the final publication in *Acta Physica Polonica* in 1999 the paper was rejected by *Physical Review C*, *Journal of High Energy Physics* and *Journal of Physics G*. Now it has more than 150 citations. This long publication history illustrates well how controversial were, and probably still are, for many of our colleagues the assumptions and the predictions of SMES.

In spite of the controversy and thanks to a strong support of Peter Seyboth, the NA49 spokesperson, the NA49 Collaboration proposed in 1997 the so-called energy scan

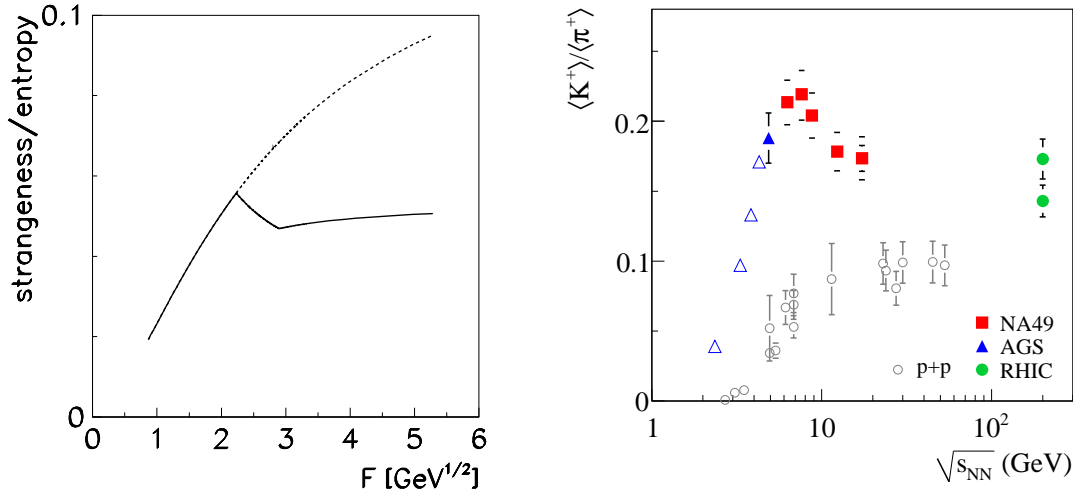


Figure 2: Left: The energy dependence of the strangeness to entropy ratio calculated with SMES (solid line). A maximum at $F \approx 2.25 \text{ GeV}^{1/2}$ ($\approx 30A \text{ GeV}$) indicates the onset of deconfinement [5]. Right: Energy dependence of the $\langle K^+ \rangle / \langle \pi^+ \rangle$ ratio measured in central Pb+Pb and Au+Au collisions (full symbols) compared to the corresponding results from $p + p$ reactions (open circles) [11].

program, at the CERN SPS. The goal of this effort was to check the SMES predictions.

The program started with two runs where data on central Pb+Pb collisions at 40A and 80A GeV were recorded in 1999 and 2000. Data at the top SPS energy of 158A GeV had already been taken in previous SPS runs. The analysis of these runs was published in [10] and the results confirmed the predictions of [5]. This finding motivated an extension of the energy scan to the lower SPS energies of 30A and 20A GeV which was completed in 2002 whereas the final results were published recently [11].

2 Remarks on the Present

The final NA49 results from the energy scan program together with reach measurements at the AGS and RHIC energies for the first time allow to check SMES predictions over a broad energy range. This section is devoted to this subject.

The SMES model is based on the assumption that the system created at the early stage (be it confined matter or a QGP) is in equilibrium and that a transition from a reaction with purely confined matter to a reaction with a QGP at the early stage occurs when the transition temperature T_C is reached. For T_C values of 170–200 MeV the transition region extends from 15A to 60A GeV [5]. Assuming the generalized Fermi-Landau conditions [5, 12] for the early stage of nucleus-nucleus collisions and a proportionality of the pion multiplicity to the early stage entropy, the ratio mean pion multiplicity to the number of wounded nucleons ($\langle \pi \rangle / \langle N_W \rangle$) increases linearly with the Fermi collision energy measure ($F \equiv (\sqrt{s_{NN}} - 2m_N)^{3/4} / \sqrt{s_{NN}}^{1/4}$) outside the transition region. The SMES prediction on the energy dependence of the early stage entropy is shown in Fig. 1 (left). The slope

parameter is proportional to $g^{1/4}$ [5], where g is the effective number of internal degrees of freedom at the early stage. In the transition region a steepening of the pion energy dependence is due to the activation of a large number of partonic degrees of freedom. This is, in fact, observed in the data on central Pb+Pb and Au+Au collisions, where the steepening starts at about 20A GeV, as shown in Fig. 1 (right). The linear dependence of $\langle\pi\rangle/\langle N_W\rangle$ on F is approximately obeyed by the data at lower and higher energies (including RHIC). An increase of the slope by a factor of about 1.3 is measured, which corresponds to an increase of the effective number of internal degrees of freedom by a factor of $1.3^4 \cong 3$, within the SMES.

The $\langle K^+\rangle/\langle\pi^+\rangle$ ratio shown in Fig. 2 (right) is approximately proportional to the total strangeness to entropy ratio which in the SMES model is assumed to be preserved from the early stage till freeze-out. At the low collision energies the strangeness to entropy ratio increases steeply with the collision energy, due to the low temperature at the early stage ($T < T_C$) and the high mass of the strangeness carriers in the confined state (the kaon mass, for instance, is 500 MeV). When the transition to a QGP is crossed ($T > T_C$), the mass of the strangeness carriers is significantly reduced to the strange quark mass of about 100 MeV. Due to the low mass $m < T$, the strangeness yield becomes (approximately) proportional to the entropy, and the strangeness to entropy (or pion) ratio is independent of energy. This leads to a decrease in the energy dependence from the larger value for confined matter at T_C to the QGP value. Thus the non-monotonic energy dependence of the strangeness to entropy ratio is followed by a saturation at the QGP value. The predicted behavior is shown in Fig. 2 (left). Such anomalous energy dependence can indeed be seen in Fig. 2 (right) and is, within the SMES, a direct consequence of the onset of deconfinement taking place at about 30A GeV.

In the mixed phase region the early stage pressure and temperature are independent of the energy density [5]. Within SMES this causes a step like dependence of the pressure and temperature on the collision energy, see Fig. 3 (left) for illustration. Consequently, this should lead to the weakening of the increase with energy of the inverse slope parameter T or, equivalently, the mean transverse mass $\langle m_T \rangle$ in the SPS energy range [13]. This qualitative prediction is confirmed by the results shown in Fig. 3 (right).

3 Remarks on the Future

Observation of the signals of the onset of deconfinement in central Pb+Pb collisions at the low SPS energies leads to new experimental and theoretical questions. Among experimental challenges are:

- A confirmation of the NA49 results,
- A study of the system size dependence of the observed effects,
- A search for signals in fluctuations and correlations.

These will be addressed by several experiments planned in the CERN SPS energy range: NA61 at the CERN SPS [14], STAR and PHENIX at the BNL RHIC [15], MPD at JINR NICA [16] and CBM at FAIR SIS-300 [17].

Among new theoretical questions are:

- What is the mechanism of the early stage equilibration?

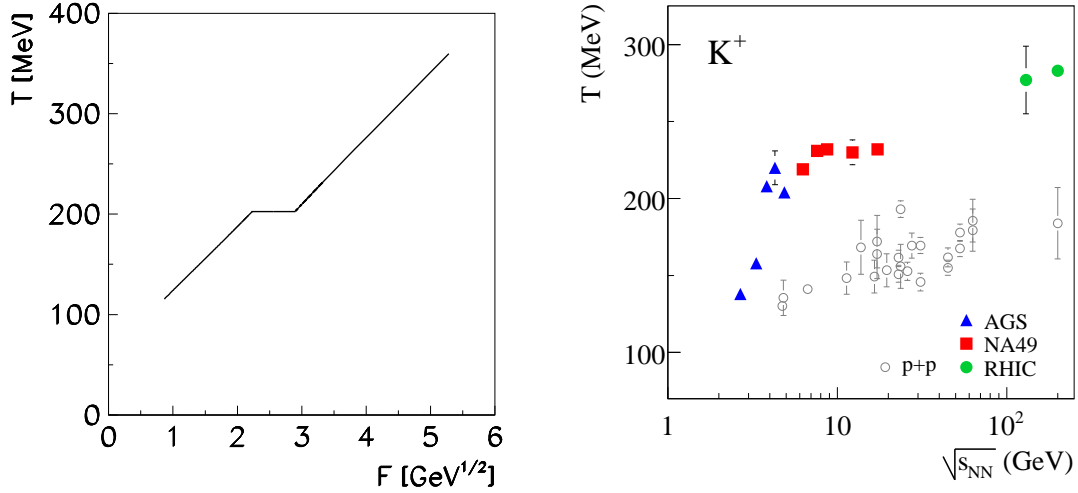


Figure 3: Left: The energy dependence of the early stage temperature calculated with SMES (solid line). A change of the slope at $F \approx 2.25$ GeV^{1/2} ($\approx 30A$ GeV) indicates the onset of deconfinement [5]. Right: Energy dependence of the inverse slope parameter of the transverse mass spectra for K^+ mesons measured in central Pb+Pb and Au+Au collisions (full symbols) compared to the corresponding results from $p + p$ reactions (open circles) [11].



Figure 4: Mark (the second from the left) with his friends and collaborators in Bergen, 2005.

- What is the structure of the transition line (cross-over, the critical point, 1st order phase transition, ...)?
 - How can this structure be established experimentally?
- In particular, the last two questions attract Mark's attention.

Recently, Mark returned to the quark-gluon bag model formulated by him in the 80s

[19] and together with his collaborators he suggested an unusual structure of the transition line [20]. I hope Mark will continue this development and will try to predict the resulting experimental signals.

Furthermore, he initiated [18] and now leads with his collaborators (see about papers of Mark et al. on this subject) the pioneering study of fluctuations in relativistic gases. This effort resulted in predictions of many new effects related to the conservation laws, quantum statistics and the finite volume of hadrons. These predictions define a base-line with respect to which effects related to the onset of deconfinement [21] and the critical point can be looked for.

Let me finish by a simple wish:

Dear Mark, just continue ...

I would like to thank the organizers of the conference New Trends in High Energy Physics (Yalta, Crimea, September 15-22, 2007) for the interesting and inspiring meeting. This work was supported by the Virtual Institute VI-146 of Helmholtz Gemeinschaft, Germany.

References

- [1] J. Rafelski and B. Muller, Phys. Rev. Lett. **48**, 1066 (1982).
- [2] T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).
- [3] J. Bartke *et al.* [NA35 Collaboration], Z. Phys. C **48**, 191 (1990).
- [4] C. Baglin *et al.* [NA38 Collaboration], Phys. Lett. B **220**, 471 (1989).
- [5] M. Gazdzicki and M. I. Gorenstein, Acta Phys. Polon. B **30**, 2705 (1999).
- [6] M. Gazdzicki and M. I. Gorenstein, Phys. Rev. Lett. **83**, 4009 (1999).
- [7] M. Gazdzicki, M. I. Gorenstein and D. Roehrich, arXiv:hep-ph/0006236.
- [8] M. Gazdzicki and M. I. Gorenstein, Phys. Rev. Lett. **83**, 4009 (1999).
- [9] M. Gazdzicki and D. Roehrich, Z. Phys. C **65**, 215 (1995).
M. Gazdzicki and D. Rohrich, Z. Phys. C **71**, 55 (1996).
- [10] S. V. Afanasiev *et al.* [The NA49 Collaboration], Phys. Rev. C **66**, 054902 (2002).
- [11] C. Alt *et al.* [NA49 Collaboration], arXiv:0710.0118 [nucl-ex].
- [12] E. Fermi, Prog. Theor. Phys. **5**, 570 (1950),
L. D. Landau, Izv. Akad. Nauk SSSR, Ser. Fiz. **17**, 51 (1953).
- [13] M. I. Gorenstein, M. Gazdzicki and K. A. Bugaev, Phys. Lett. B **567**, 175 (2003).
- [14] N. Antoniou *et al.* [NA61 Collaboration], CERN-SPSC-P-330
- [15] G. S. F. Stephans, J. Phys. G **32**, S447 (2006).
- [16] A. N. Sissakian, A. S. Sorin and V. D. Toneev, arXiv:nucl-th/0608032.
- [17] P. Senger, T. Galatyuk, D. Kresan, A. Kiseleva and E. Kryshen, PoS C **POD2006**, 018 (2006).
- [18] V. V. Begun, M. Gazdzicki, M. I. Gorenstein and O. S. Zozulya, Phys. Rev. C **70**, 034901 (2004).
- [19] M. I. Gorenstein, S. I. Lipskikh and G. M. Zinovev, Z. Phys. C **22**, 189 (1984).
- [20] M. I. Gorenstein, M. Gazdzicki and W. Greiner, Phys. Rev. C **72**, 024909 (2005).
- [21] M. Gazdzicki, M. I. Gorenstein and S. Mrowczynski, Phys. Lett. B **585**, 115 (2004)
and // M. I. Gorenstein, M. Gazdzicki and O. S. Zozulya, Phys. Lett. B **585**, 237 (2004).